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USE OF RADIOACTIVE ISOTOPES FOR DETERMINING ATMOSPHERIC TURBULENCE

[Following is the translation of an article by N. N. Aleksandrov in Trudy Arkticheskogo i Antarkticheskogo Nauchno-Issledovatel'skogo Instituta -- Voprosy fiz. pogranichnogo slova atmosfery v Arktike (Trans. of the Arctic and Antarctic Scientific Research Institute -- Problems of the Physical Boundary Layer of the Atmosphere in the Arctic Regions), No. 226, Leningrad, 1959, pages 113-122.]

The semiempirical theories of turbulence developed both by national and foreign research investigators are now being used for the determination of the characteristics of turbulent exchange between the earth's surface and the atmosphere. The turbulence coefficient and all other characteristics (such as tangential stress, mixing path, dynamic velocity and so forth) are determined from the measurements of profiles of the meteorological elements. The calculation procedure developed, and the order in which the measurements are made, yield satisfactory results for relatively simple cases (level terrain with a homogeneous base surface, sufficiently high wind velocity, and so forth).

The determination of the turbulence coefficient for a nonhomogeneous base surface on the basis of these methods, on the other hand, is beset with substantial difficulties. Hence the methods of determining the turbulence coefficient without resorting to the numerous assumptions on which the above-mentioned methods are based, are of substantial interest. It should be noted that the methods formerly used to determine the turbulence coefficient which took into account the vertical distribution of emanation and its decay products /2, 10/ and the ion concentration from a plane and linear ionization source /11/, as well as the methods utilizing the results of observation of an expanding smoke cloud /3, 4, 9/, have not acquired widespread application.

In the first two cases, this can be explained by the complexity of the sampling procedure and the analysis of samples. As to the observations of a smoke cloud,

substantial errors occur in determining initial data. Moreover, in the expansion of a smoke cloud, which is a turbid medium, the actual turbulence pattern is distorted owing to radiation absorption by the smoke particles.

Progress achieved in studying and applying radioactive isotopes, as well as the present, refined technique of measuring ionizing radiation, permits determination of the turbulent diffusion coefficient on the basis of the concentration of a passively transferred substance measured with the use of tagged atoms.

Such a method of determining concentration has many advantages namely:

1. Sampling and analysis of air is no longer necessary.
2. Initial data are determined with greater exactness.
3. Continuous measurement of concentration at given points in a radioactive cloud is provided for.
4. At small concentrations of radioactive impurity, a practically transparent cloud forms which does not absorb radiation and thus does not disturb the character of diffusion.

In the present work, we attempt to demonstrate that it is possible to measure the concentration of a passively transmitted substance tagged by radioactive atoms, by means of gas-discharge counters.

We know that the association between the radioactive nuclei q_1 and q_2 in two objects under investigation, and the number of the β-particles or γ-photons counted /12/, is expressed by the relation

$$\frac{q_1}{q_2} = \frac{n_1}{n_2}. \qquad (1)$$

provided that the following conditions are satisfied:

1. The radiations of the radioactive isotopes in the two objects under comparison possess the same β-particle energy spectrum or the same magnitudes of γ energy quanta.
2. The numbers of β-particles or γ-quanta emitted in the disintegration of the same number of nuclei in the two objects are equal.
3. The geometrical dimensions of the objects under comparison are the same.
4. The radioactive nuclei in the objects under comparison are distributed uniformly or similarly.
5. The locations of the objects under comparison relative to the counters are the same.

If the above conditions for a radioactive cloud

under investigation are satisfied, it is possible to observe the concentration of the radioactive impurity as it varies under the influence of turbulent diffusion, as the number of β-particles registered at several points. Then, if we possess the data based on the diagrams of E. S. Lyapin /9/ on the distribution of radioactive impurity concentration, it is possible to determine the coefficient of turbulent diffusion.

It is possible to realize the above conditions if the radioactive cloud contains one isotope that emits β-particles only, and if the cloud is introduced into the air in the form of an aerosol consisting of particles of less than one micron in diameter. The dimensions of the cloud should exceed the maximum path length of the β-particles. Thus the counters placed within a given cloud will register the β-particles from equal "counter volumes" whose locations relative to the counters are the same. By "counter volume" we mean the volume of a sphere whose radius is equal to the sum of the maximum path length of the β-particles of a given radioactive cloud, and the radius of the working volume of a spherical counter.

Since the radioactive decay of different substances is accompanied by different types of emission, the choice of a radioactive tracer is of great significance. Evidently, the tracer selected must satisfy the following requirements:

1. It should develop smoke.
2. In developing smoke, it should produce a cloud of radioactive smoke consisting of particles of less than one micron in diameter, which form a stable aerosol.
3. Its half life should be such as to eliminate any appreciable variation of activity during the requirements.
4. There should be no chemical reaction between the tracer and the medium which might affect the composition of the cloud.
5. The tracer should not accumulate in living organisms.
6. Its ionization density in biological tissues should be small.
7. Its radiation should be measurable with ordinary gas-discharge counters.

At present, we know of about 40 isotopes that decay yielding β-radiation only; however, only a few of these isotopes more or less satisfy our other requirements. One such isotope is phosphorus-32, which we chose as our tracer.

Let us now examine the problem of whether the

concentration of a radioactive cloud can be measured by means of gas-discharge counters. Suppose we have a radioactive cloud that expands from a point source in the direction of the wind. At a certain distance x from the source, we have a radiation counter which is a sphere of radius r_0 and cross section $s_{counter}=\pi r^2$. The concentration of the radioactive cloud within the limits of the counter volume of a given counter, is considered constant.

Let us denote the mean concentration of the radioactive nuclei within the counter volume by q, and the number of β-particles corresponding to the given concentration and emitted per unit time, by n_o. Actually, n_o is a function of x, y, z, k_x, k_y, k_z and n, however, since the dependence of n_o on y, z, k_x, k_y, k_z and n diminishes with increasing x when $x_{initial}$ is sufficiently large, we will consider n_o constant.

The variation of n_o with time may be neglected, since the variation of activity due to radioactive decay during the experiment is infinitesimal. In this case, the flow of β-particles from the elementary volume dv within the solid angle 2π is expressed as follows:

$$dN_0 = n_0 dv, \qquad (2)$$

where

$$dv = r^2 \cdot \sin\theta \, d\theta \, d\varphi \, dr.$$

In order that one β-particle be registered by a counter, it is sufficient that its path cross or terminate in the counter's sensitive volume /8/. Hence, the counter registers only that part of the flow equal to

$$dN = \frac{\omega}{4\pi} n_0 dv, \qquad (3)$$

where $\omega = S_{counter}/r^2$ is the solid angle at which the sensitive volume of the counter may be seen from the elementary volume dv (r being the distance of this elementary volume from the counter).

If we allow for the attenuation of radiation in the medium and at the walls of the counter, the expression (3) will take the form

$$dN = \frac{S_{cr} n_0 e^{-\mu'(d_{cr}+d_w+d_{mp})}}{4\pi r^2} dv, \qquad (4)$$

where $\mu' = \frac{\mu}{\rho}$ is the mass absorption coefficient (cm^2/g)

and $d'_{counter} + d'_{air} + d'_{imput} = d'$ is the total thickness of the absorbing layers; in this case, $d'_{counter} = \rho_{counter} d_{counter}$ is the thickness of the counter walls in g/cm^2; $d'_{air} = \rho_{counter} r$ is the thickness of the air layer in g/cm^2; $d'_{impur} = \rho_{impur} r$ is the thickness of the layer of the radioactive impurity in g/cm^2.

The aerosol density ρ_{impur} is usually much lower than the air density (for example, the mean effective density of an aerosol consisting of phosphoric acids /5/ is equal to $\rho_{impur} = 0.61 \times 10^{-5}$ g/cm^3). Hence, the last item in the exponent of equation (4) may be neglected. If we express $d'_{counter}$ in terms of the equivalent thickness of the air layer, under the condition that $\rho_{counter} d_{counter} = \rho_{air} d_{air}$, then (4) takes the following form:

$$dN = \frac{S_{sp} n_0 e^{-\mu' \rho_a d_a - \mu' \rho_a r'}}{4\pi r^2} d\omega. \qquad (5)$$

Integrating the expressions (2) and (5) with respect to r, ϑ and φ, within the limits of r_0 to R, 0 to $\pi/2$, and 0 to π, respectively, we obtain the total number of β-particles emitted from the sphere with radius R, as

$$N_0 = \frac{4}{3} \pi n_0 (R - r_0)^3, \qquad (6)$$

as well as the number of β-particles that should actually reach the working volume of the counter as a result of absorption and attenuation by the medium,

$$N = \frac{S_{sp} n_0}{\mu' \rho_a} \left[e^{-\mu' \rho_a (d_a + r_0)} - e^{-\mu' \rho_a (R + d_a)} \right]. \qquad (7)$$

Introducing the correction for the counter "dead time" /6/ $N = n/1 - n\tau$, where τ is the counter "dead time," n is the number of β-particles registered by the counter, and N is the number of β-particles that reach the sensitive volume of the counter, we obtain

$$n = \frac{S_{sp} n_0 (1 - n\tau)}{\mu' \rho_a} \left[e^{-\mu' \rho_a (d_a + r_0)} - e^{-\mu' \rho_a (R + d_a)} \right]. \qquad (8)$$

The ratio of equation (8) to equation (6) is the yield

coefficient of the given counter, which characterizes the relation between the measured and actual number of β-particles within the volume under investigation. Denoting the yield coefficient as y(R), we get

$$y(R)=\frac{n}{N_0}=\frac{3}{4}\cdot\frac{r_0^2(1-n\varepsilon)}{(R-r_0)^2\mu'\rho_a}\left[e^{-\mu'\rho_a(d_a+r_0)}-e^{-\mu'\rho_a(R+d_a)}\right]. \quad (9)$$

We know that the actual absorption curve departs appreciably from the exponential law. It reaches its maximum value not at R = ∞ but at a certain definite value R, equal to $R_{counter}$:

$$R_{cч}=d_m-d_a+r_0,$$

where d_m is the maximum path length of a β-particle (cm), d_{air} is the equivalent thickness of the air layer (cm); r_0 is the radius of the counter's sensitive volume (cm).

The value $R=R_{counter}$, the smallest R for which β-particles no longer reach the sensitive volume, we will call the radius of the counter volume. If the dimensions of the radioactive cloud exceed the magnitude of the counter volume, then, obviously, the number of the β-particles registered no longer depends on further increases in the size of the radioactive cloud, and is determined solely by the cloud concentration, -- i.e., the condition $\frac{q_1}{q_2}=\frac{n_1}{n_2}$ (1), is satisfied.

Hence, the concentration may be judged from the number of β-particles registered. The quantity y(R) can be determined from the ratio of the ordinates of the actual absorption curve and the tangent to it, corresponding to the point $R + R_{counter}$, or, approximately, from Formula (9), provided that R is replaced by $R_{counter}$ and the second term in the exponent is set equal to zero. In practice, we will determine y(R) by means of Formula (9), since obtaining the actual absorption curve for the 4π count conditions is beset with substantial difficulties.

The activity in the counter volume,

$$A=\frac{n}{3{,}7\cdot10^7 y_3}\ (\text{Кюри}) \quad (10)$$

can be determined from the known value of the yield

coefficient y and the number n of β-particles registered, where σ is the yield of β-particles per disintegration event.

The mean activity concentration in the counter volume can be determined from the expression (8):

$$a = \frac{\mu' \rho_a e^{\mu' \rho_a (d_a + \gamma)}}{3{,}7 \cdot 10^7 \cdot S_{cq} \sigma (1 - \pi\tau)} \cdot n \quad \left(\frac{\text{millicuries}}{\text{cm}^3}\right) \tag{11}$$

It should be noted that it is possible to control the magnitude of the counter volume within the required limits by the use of additional aluminum hoods, whose necessary thickness may be computed from the formulas

$$d_a = \frac{8{,}58}{\mu' \rho_a} - R_{cq}, \tag{12}$$

where d_{air} is the equivalent thickness of the air layer, and

$$d_{Al} = d_a \frac{\rho_a}{\rho_{Al}}, \tag{13}$$

where d_{Al} is the thickness of the aluminum hood.

This formula is obtained from the expression (8) under the condition that

$$e^{-\mu' \rho_a (R_{cq} + d_a)} = 0{,}0002, \tag{14}$$

i.e., that $n\big|_{R=R\ \text{counter}}$ differs from $n\big|_{R=\infty}$ by approximately 0.1%.

However, the yield coefficient decreases with decreasing counter volume, and this leads to the necessity of increasing considerably the activity concentration of the radioactive cloud.

Let us now calculate the conditions for an experiment determining the concentration distribution in a radioactive cloud. We will determine:

(a) the necessary source strength of the radioactive cloud;

(b) the dimensions of the dangerous zone;

(c) the dimensions of the experimental zone.

To facilitate computation, let us introduce the following concepts:

1. The maximum range of activity concentration

$$M = \frac{a_{max}}{a_{min}}, \tag{15}$$

where a_{max} and a_{min} are the maximum and minimum volumetric

concentrations in the counter volume, that can be measured by the counter. These quantities are determined by means of formula (11) from the maximum and minimum values of the counter capacity for a given instrument.

2. The dilution coefficient

$$L = \frac{a_{max}}{a_{min}} \cdot \frac{a_{initial}}{a_{final}} \qquad (16)$$

where $a_{initial}$ and a_{final} are the initial and final volumetric activity concentrations.

The dilution coefficient is selected in conformity with the given experiment. Here, in order to obtain reliable readings, a_{final} should be selected in such a manner than the corresponding counter capacity n_{final} is at least twice as large as the background capacity $n_{background}$.

Similar to quantities a_{max} and a_{min}, a_{final} is calculated from formula (11). Obviously, the condition

$$L \leqslant M$$

should be satisfied.

The source strength and the dimensions of the dangerous zone and experimental zone can be rated by use of the corresponding Sutton formulas /1, 14/. These formulas permit determination of:

(a) the smoke concentration from a continuous point source,

$$q = \frac{Q}{\pi c_y c_z u \cdot x^{2-n}} \cdot e^{-\frac{1}{x^{2-n}}\left(\frac{y^2}{c_y^2} + \frac{z^2}{c_z^2}\right)}, \qquad (17)$$

where q is the concentration at the points x, y, z,
Q is the source strength,
u is the mean velocity of the wind,
c_y and c_z are the virtual diffusion coefficients,
and n is a dimensionless parameter accounting for the stratification of the atmosphere:

(b) the width of the cloud from a continuous point source,

$$2y_0 = 2(\ln 10)^{\frac{1}{2}} \cdot c_y \cdot x^{1-\frac{1}{2}n}; \qquad (18)$$

(c) the height of the cloud from a continuous point or linear source,

$$z_0 = (\ln 10)^{\frac{1}{2}} \cdot c_z \cdot x^{1-\frac{1}{2}n} \qquad (19)$$

In planning the experiment, we will proceed from the conditions for equilibrium stratification for which, according to P. I. Andreyev /1/, $c_y=c_z$ and n=0. Here, using Sutton's formulas, we obtain the calculation outline of the experiment, consisting of the following basic steps:

1. We determine the minimum distance of the radiation counter from the source, at which the counter volume remains within the limits of the cloud, from the formula

$$x_{min}=\frac{R_{ct}}{\frac{1}{(\ln 10)^{\frac{1}{2}}}c_y}, \qquad (20)$$

which is obtained from equation (18) by substituting $R_{counter}$ for y_0;

2. We compute the distance $x_{initial}$ for which, in the counter volume n_0 may be considered constant, from

$$x_{min}=\frac{R_{ct}}{c_y}\sqrt{10}. \qquad (21)$$

Formula (21) is obtained from expression (17), under the condition that

$$e^{-\frac{1}{2n}\left(\frac{R_{ct}}{c_y}\right)^2}=e^{-0.1},$$

i.e., that the boundary concentration of the counter volume differs from the axial concentration by 0.1.

3. We determine the maximum range of activity concentration , M, from formula (11) for the maximum and minimum values of n.

4. We calculate the source strength for the values obtained for $x_{initial}$ and $a_{initial}$ as well as the selected mean velocity of the wind, from equation (17) solved with respect to

$$Q=\frac{\pi\cdot a_{min}\cdot c_y\cdot c_z\bar{u}x^2_{min}}{2}\cdot e^{\frac{1}{2}\left(\frac{y^2}{c_y^2}+\frac{z^2}{c_z^2}\right)} \text{ mg-equiv/sec} \qquad (22)$$

5. We determine the ultimate boundary of the zone if experiment from the formula

$$x_k=x_{min}\sqrt{\frac{a_{min}}{a_x}}^{\frac{1}{n+2}} \qquad (23)$$

*Since the source is located on the ground, the value for the concentration obtained for the same source strength is twice /that for a source radiating spherically/.

which is obtained from the ratio of the axial concentrations according to the expression (22) at the points $x_{initial}$ and x_{final}, where y=z=0. Here, we select $a_{final} = 2a_{background}$, i.e., L M.

6. We determine the extent of the dangerous zone. The permissible concentrations of radioactive aerosols in workshops are to be found in the "Handbook on Radioactive Radiations and Protection" /7/. For settlements, these values should be reduced tenfold. Substituting in expression (23) $a_{permissible}$ for a_{final}, we obtain the boundary of the dangerous zone, $x_{permissible}$, in the direction of the wind. The extension of the dangerous zone perpendicular to the wind $y_{permissible}$ may be determined from the following Sutton formula /13/:

$$2y_0 = 2\left(\ln\frac{100}{p}\right)^{\frac{1}{2}} c_y x_{max}^{1-\frac{1}{2}n}, \qquad (24)$$

where p is the value for the axial concentration in percent, n=0, and $y_0 = y_{permissible}/2$.

Obviously, the dimensions of these zones depend to a great extent on the degree of turbulence and wind velocity; hence, it should be mandatory to define accurately the initial data prior to the experiment, particularly in determining the boundary of the dangerous zone.

The calculation of the necessary source strength and of the boundaries of the dangerous zone may serve as an example. Suppose we have a spherical counter with radius r_0=6.33 cm, a wall thickness $d_{counter}$=0.05 cm and a wall-material density ρ=2.6 g/cm^3; then the thickness of the air layer whose absorption capacity is equivalent to that of the walls of the counter will equal

$$d_x = \frac{2{,}6 \cdot 0{,}05}{0{,}00129} = 100{,}7 \text{ cm}.$$

Since for phosphorus-32 μ equals 10.85, at n_{min}= 1 pulse per second the minimum concentration of a radioactive cloud measurable with a given counter, according to Formula (11) will be equal to

$$a_{min} = \frac{10{,}85 \cdot 0{,}00129 \cdot 1 \cdot e^{10{,}85 \cdot 0{,}05(100{,}7+6{,}33)}}{3{,}7 \cdot 10^7 \cdot 40} = 4{,}3 \cdot 10^{-11} \text{ curie/cm}^3$$

Whence, according to the diagram cited above, we obtain

$$x_{min} = \frac{5,13}{1,5 \cdot 0,05} = 68,4 \text{ м.}$$

$$x_{max} = \frac{5,13}{0,05} \cdot 3,16 = 324,2 \text{ м.}$$

If $a_{min} = 4.3 \times 10^{-11}$ μ curie/cm^3, and M = 1,000, then

$$a_{max} = 4,3 \cdot 10^{-5} \text{ μ curie/cm}^3$$

At u = 3.5 m/sec

$$Q = \frac{3,14 \cdot 0,0025 \cdot 3,5 \cdot 324,2^2 \cdot 4,3 \cdot 10^{-2}}{2} = 62,2 \text{ μ curie/sec}$$

$$a_{\text{к пит}} = a_{min} = 4,3 \cdot 10^{-11} \frac{\text{μ curie/cm}^3}{\text{микропроток}^3}; \; L = 100,$$

$$x_{\text{к пит}} = 324,2 \cdot \sqrt{100} = 3242 \text{ м,}$$

$$2y_{\text{к пит}} = 2\left(\ln \frac{100}{0,001}\right)^{\frac{1}{2}} \cdot 0,05 \cdot 3242 = 737 \text{ м.}$$

According to the tables, $a_{suppl} = 10^{-10}$ μ curie/cm^3, whence

$$x_{\text{доп}} = 324,2 \frac{4,3 \cdot 10^{-6}}{10^{-10}} = 6940 \text{ м,}$$

$$y_{\text{доп}} = 2\left(\ln \frac{100}{0,001}\right)^{\frac{1}{2}} \cdot 0,05 \cdot 6940 = 2240 \text{ м.}$$

For a counter with radius r_o=a cm, $a_{min} = 1.24 \times 10^{-10}$ μ curie/cm^3.

This makes it necessary to increase the source strength approximately tenfold in order that the activity-dilution range L=100 which we measure be maintained, while this, in turn, expands the boundaries of the dangerous zone up to x_{suppl} = 11,411 m and y_{suppl} = 3,685 m, the dimensions of the test zone being the same as for the counter with r_o = 6.33 cm.

On 7 September 1956, an experiment on the scattering of radioactive impurities was conducted at the ice-floe station "North Pole." The diagram of the experiment is shown in Fig. 1. The radioactive cloud was obtained by burning 0.59 g phosphorus-32 with a total activity of 1.4 μ curie. The burning of the phosphorus lasted 30 sec; hence the source strength Q was approximately equal to 0.047 μ curie/sec. The mean velocity of the wind was 3.5 m/sec. The measurement results are presented on the

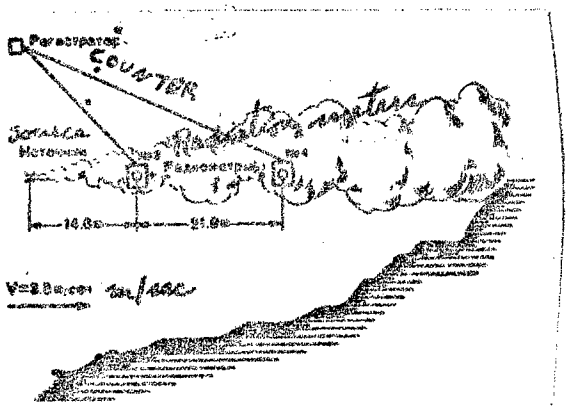

Fig. 1. Diagram of experiment on the scattering of radioactive impurities at the "North Pole 4" station.

chart (Fig. 2) whose recording speed was 6 mm/sec.

Fig. 2. Sample of the recording of radiation intensity from a radioactive impurity cloud. (1) Radiation meter No 4; (2) radiation meter No. 3.

In the present experiment STS-8 cylindrical counters were used, for lack of spherical counters. This should not have essentially affected the measurement results, provided that the conditions required by relation (1), i.e., $V'_{cloud} \gg V_{counter}$, were satisfied. Hence, the calculation for the cylindrical counters was made using the formulas for a spherical counter with a sensitive volume equal to that of a cylindrical counter. For an STS-8 tube, whose sensitive volume $v=34$ cm^3, the radius of an equivalent spherical counter is $r_0=2$cm.

Since our possibilities were limited by the dimensions of the ice floe and the direction of the wind, the radiation meters Nos. 3 and 4 were considerably closer to the source of the radioactive cloud than was required by the above calculation. The distances of the radiation meters 3 and 4 from the source of the radioactive cloud were $x_{initial} = 14.6$ m and $x_{final} = 36.5$ m, respectively (Fig. 1).

The activity concentrations calculated at the points

$x_{initial}$ = 14.6 m, x_{final} = 36.5 m, for z = 0.5 m and a source strength of Q = 0.047 μ curie/sec, were $a_{initial}$ = 1.1 X 10^{-8} curie/cm^3 and a_{final} = 0.25 X 10^{-8} μ curie/cm^3, respectively, while the lateral dimensions of the cloud for the given $x_{initial}$ and $x_{ultimate}$ were $2y_{initial}$ =2.98 and $2y_{ultimate}$ = 6.89 m, respectively.

Such concentrations of a radioactive cloud are readily accessible to measurement by means of radiation meters, provided that the lateral dimensions of the cloud for the given $y_{initial}$ and $y_{ultimate}$ exceed the radius of the counter volume, $R_{counter}$. However, in the present case $R_{counter}$ = 5.13 m, so that the readings of the radiation meters could not correspond to the actual values of the mean concentration at the points under investigation.

Nevertheless, the experiment carried out at the "North Pole 4" station to determine in principle whether it is possible to measure the concentration of radioactive impurities and the calculations discussed above, revealed the following:

1. At a minimum source strength of Q = 0.047 μ curie/sec, the radiation from a radioactive cloud can be measured by means of ordinary gas-discharge counters and, hence, the concentration of the radioactive impurity can be measured provided that condition (1) is satisfied.

2. If we know the law of the distribution of concentration in the counter volume, it is possible to obtain an objective concentration characteristic also in the zone form x_{min} to $x_{initial}$; this would essentially permit a decrease in the necessary source strength and, consequently, in the dangerous zone of the experiment.

3. When the experiment is set up correctly, and its preliminary and final conditions are calculated, the concentration measurements themselves are rather simple and reliable.

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